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A Structural Damping Technique Based on Coupling Structures with Electronic Circuits

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13. ABSTRACT *(Maximum 200 words)*
This project investigated a novel active structural damping technique using PZT (lead zirconate titanate) patches as actuators/sensors and the internal resonance and saturation phenomena of multiple degree-of-freedom systems to suppress transient and steady-state vibrations of structures. The strategy consists of introducing second-order controllers and coupling them to the structure through a sensor and an actuator, where both the feedback and control signals are quadratic. Analytical, numerical, and experimental tasks have been performed to verify and demonstrate the efficiency of this technique. In the experiments, we successfully controlled the vibrations of a DC motor with a rigid bar attached, single-mode vibrations of beams, transient and steady-state vibrations of beams, multimode vibrations of beams using multiple electronic circuits, vibrations of skew cantilever plates, and machine-tool chatter by using analog and digital control systems. Moreover, we have derived and experimentally verified new nonlinear vibration absorbers using 2:1, 3:1, 4:1, and 4:2:1 internal resonances.

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## I. PROBLEM STATEMENT

This project investigates a new nonlinear structural damping technique using internal resonances and saturation phenomena to suppress transient and steady-state vibrations of flexible structures. The technique exploits modal interactions and the saturation phenomenon arising from internal resonances to transfer energy from a vibrating structure to one or more electronic circuits or digital controllers. For structures subjected to resonant excitations, the technique exploits the saturation phenomenon exhibited by multiple degree-of-freedom systems coupled with quadratic nonlinearities and possessing two-to-one autoparametric resonances. The strategy consists of introducing a series of second-order controllers and coupling them with the structure through an actuator and a quadratic feedback control law. Once the structure is excited near its resonances, the responses of the excited modes saturate and the vibration energy is channeled into the controllers.

Another approach to improve performance in a control system is to increase the number of sensors used, but this is often impractical due to cost and communication problems. To overcome this limitation, a vibration suppression technique is developed that uses a scanning laser Doppler vibrometer as a sensor. Control experimentation is performed in which a scanning laser and a piezoceramic patch are used simultaneously for sensing, and separate piezoceramic patches are used for actuation. This hybrid approach is advantageous because the structural velocity at many locations is measured, and when the velocity is maximum the strain is zero, and conversely. Because many states are measured, the technique may also be used for structural damage detection.

## II. SUMMARY OF RESULTS

**1) North Carolina A&T State University and University of Missouri-Columbia:**
To test and validate this saturation control method and other new designs, a digital control system was built. The system consists of SIMULINK modeling software and a dSPACE DS1102 controller system in a pentium computer. The SIMULINK software is used to build the control block diagrams, and then the dSPACE Real-Time Workshop is used to generate a C-code model from the SIMULINK model. The C-code model is then connected by the dSPACE Real-Time Interface to the dSPACE real-time hardware system for hardware-in-the-loop simulation.

This saturation control method has been studied theoretically and experimentally for suppressing the first-mode, second-mode, and third-mode vibrations of a 16.53"x2.5"x.0502" cantilevered stainless steel beam using two 1.81"x0.81"x.01" PZT (lead zirconate titanate) patches for control actuation and one such patch for sensing. A method of estimating the excitation force caused by the bending of an integrated PZT patch has been developed. Perturbation analyses, direct numerical integration, and experiments have been performed to understand the working mechanism of this 2:1 saturation controller, to evaluate its efficiency and robustness, and to compare it with the

conventional linear vibration absorber. Results show that this 2:1 saturation controller is efficient and robust in controlling forced harmonic vibrations. The 2:1 saturation controller is shown to be an indirect position-feedback controller, and it is more robust and efficient than a direct position-feedback controller. Moreover, the saturation controller is also able to suppress large-amplitude vibrations. However, its effective frequency bandwidth is narrow, and it cannot exactly drive the vibration to zero because of the static component in the quadratic coupling term. Although the saturation controller also works in controlling transient vibrations, it is inconvenient for use and is not as efficient as a simple linear position-feedback control method. A hybrid controller consisting of a 2:1 saturation controller and a linear position-feedback controller is shown to be robust and efficient in controlling steady-state and transient vibrations.

The working mechanism of the original 2:1 saturation controller was uncovered during the study of the cantilever stainless steel beam, and it was used to design a refined 2:1 nonlinear vibration absorber using a direct velocity feedback and a quadratic velocity coupling term. Results show that the use of the quadratic velocity coupling makes it possible to completely stop the vibration under resonant excitations. Moreover, the effective frequency bandwidth of the new nonlinear absorber can be increased by increasing the quadratic velocity coupling gain, and the linear velocity feedback significantly increases the damping effect in controlling transient vibrations. Results also show that the conventional linear vibration absorber splits a system frequency into two causing spillover effects in control, its response amplitude increases with the excitation amplitude at a fixed excitation frequency, and its response amplitude changes nonlinearly when the excitation frequency changes. On the other hand, the new 2:1 nonlinear vibration absorber does not split a system frequency into two, its response amplitude remains constant at a fixed excitation frequency when the excitation amplitude changes, and its response amplitude changes linearly when the excitation frequency changes

The 2:1 saturation controller has also been studied theoretically and experimentally for suppressing the first-mode, second-mode, and third-mode vibrations of a 19.63"x12.16"x4.63"x.122" cantilevered skew aluminum plate using one 1.81"x1.31"x.01" PZT patch for control actuation and one 1.81"x0.81"x.01" PZT patch for sensing. Because of the non-rectangular geometry, all vibration modes are bending-torsional vibrations. Although only a bending moment is applied through the integrated PZT actuator in controlling the modal vibrations, the vibrations are successfully suppressed. Hence this saturation controller should be able to control, by applying only bending moments, other bending-torsional vibrations of structures due to irregular geometry and/or anisotropy. The third mode of the plate is dominated by torsion. A PSV-200 scanning laser vibrometer was used to observe the third mode shape under the control action. It was found that the mode shape was not changed by the control action. Moreover, guidelines for designing saturation controllers, operational conditions, and effective frequency bandwidths have been derived.

To investigate the control of torsional structural vibrations, nonlinear finite element analyses of trusses subjected to bi-moments and extensional loads induced by integrated PZT patches have been performed. Results show that a 90° or non-parallel bi-moment

created by appropriately arranged PZT patches is more efficient than a 180° bi-moment in controlling torsional vibrations. However, beams may not behave exactly the same as the studied trusses in torsion. The torsional deformation of structures induced by integrated PZT patches requires further study.

The working mechanism of the original 2:1 saturation controller has been applied to the design of several new nonlinear vibration absorbers using displacement and/or velocity feedback, higher-order nonlinearities, and the corresponding saturation phenomena. Nonlinear vibration absorbers using quadratic, cubic, and/or quartic nonlinearities to introduce 2:1, 3:1, 4:1, and 4:2:1 internal resonances to the structure have been studied numerically and experimentally in controlling the 19.63"x12.16"x4.63"x.122" cantilevered skew aluminum plate. Results show that the stability of the 3:1 nonlinear vibration absorber depends on the initial conditions because the cubic nonlinearity does not have the static component that the quadratic nonlinearity has. Moreover, when the initial values of the controller in the 4:1 nonlinear vibration absorber are small, the controller takes a long time to grow before it can suppress the structural vibration. Based on these observations, a 4:2:1 nonlinear vibration absorber has been designed and tested in detail. Two second-order controllers are used in the 4:2:1 vibration absorber. One has a natural frequency that is one quarter of the structural vibration frequency, and the other second-order controller has a natural frequency that is one half of the structural vibration frequency. Thus they are coupled with the structure through quadratic, cubic, and quartic nonlinearities. Numerical and experimental results show that the 4:2:1 vibration absorber is efficient in suppressing the plate vibrations.

Because there is no decision making or gain computation required in these nonlinear vibration absorbers, they can be built using simple commercial electronic circuits and can be used to regulate dynamical systems to prevent severe vibrations when they are subjected to resonant excitations. The technique can also drive steady-state vibration responses to zero without using a high gain controller as in linear control systems.

Another approach to improve the performance of a control system is to increase the number of sensors used, but this is usually impractical due to cost and communication problems. To overcome this limitation, a new smart structure concept is investigated that combines use of a Laser Doppler Vibrometer (LDV) and PZT patches. The LDV laser beam is scanned over the surface of the structure by a controlled scanning mirror and measures the velocity of the structure in the direction of the laser beam. This signal is used for direct velocity feedback in the control system. The PZT patches measure strains used for control signals or apply actuation forces to counteract structural vibration. Laser velocity sensing and PZT strain sensing can also be used simultaneously. This hybrid approach is advantageous because the structural velocity is greatest when the strain is zero (the vibration mode passes through equilibrium), and the structural strain is greatest when the velocity is zero (the vibration mode is at peak amplitude). These complementary control signals provide a more effective control action than a single sensor type because different states are measured, and when one sensor output is zero the other is at a maximum. In addition, if a single sensor were used, differentiation or integration would be required to obtain the second state. This introduces time delay and

noise into the control loop. The single sensor also cannot physically be at two locations, one where velocities are large and a different location where strains are large. In general, velocities and strains will not be the maximum at the same location on complex structures. A simply supported structure is a counter example where they could be the maximum at the same point. In the control technique proposed, strains should be measured close to the actuators because collocation provides stability for the part of the control loop with strain sensing and actuation.

There apparently are no specific control laws available in the literature for use with a movable velocity sensor such as a scanning LDV. Thus two possible control approaches were investigated based on extending classical techniques of static feedback control. The first technique computes the optimal constant gain at each spatial coordinate and then uses gain switching to apply the gain corresponding to the laser position. The second approach uses the Linear Quadratic Regulator (LQR) control method assuming a time delay in updating the state feedback vector where the delay is dependent on the scanning speed of the laser. Computer simulation of the two active damping control algorithms was performed to suppress transient and random vibrations using low control forces. The simulations used a finite-element model of a cantilever beam and showed that the gain switching controller did not have significantly better performance that the non-scanning controller. This is because only one measurement at a time is considered and the past states are not used. The second approach showed that if the laser can be scanned faster than the highest controlled natural frequency of the beam, and all the velocity states are measured, then the performance of classical linear optimal control can be achieved.

To verify the theory, a cantilever beam structure was built and the LDV sensor was tested along with other types of sensors. In the experiments, only the first vibration mode of the cantilever beam could be controlled because of a limitation in the speed of the scanning mirror used. The testing showed that a hybrid sensing technique in which the laser and a piezoceramic patch are used simultaneously for sensing, and separate piezoceramic patches are used for actuation, was the most efficient control approach. The damping ratio of the uncontrolled beam was computed based on free vibration measurements to be 0.008. With the hybrid control system, the damping ratio improved to 0.103. In these experiments, the control performance was limited by the available actuation force of the two PZT patches. The control system was also able to suppress vibration of a damaged beam with no significant loss in performance. The damage (a saw cut) was also detected by a periodic "drop-out" of the laser signal during free vibration of the cantilever beam.

Overall, the laser sensing control technique requires expensive components, but has possible general applications on structures that are large, inaccessible, require non-contact sensors, or where a large number of coordinates must be measured. With improved hardware and a new control algorithm, the technique potentially could control higher modes and simultaneously detect damage to the structure. Damage mitigation might also be able to be performed using the integrated controller design.

**2) Virginia Polytechnic Institute and State University:**
We devised strategies of suppressing high-amplitude vibrations of cantilever beams when subjected to either primary external or principal parametric resonances. Guided by results of previous investigations into the nonlinear dynamics of single- and multidegree-of-freedom structures, we designed mechatronic systems of sensors, actuators, and electronic devices and implemented nonlinear active feedback control.

In the case of external excitation, we devised two vibration absorbers based on either quadratic or cubic feedback. We conducted theoretical analysis and demonstrated that when a two-to-one (one-to-one) internal resonance condition is imposed between the plant and the quadratic (cubic) absorber, there exists a saturation phenomenon. When the plant is forced near its resonant frequency and the forcing amplitude exceeds a certain small threshold, the nonlinear coupling creates an energy transfer mechanism that limits (saturates) the response of the plant.

Our theoretical studies revealed that the cubic absorber creates regimes of high-amplitude quasiperiodic and chaotic responses, thereby limiting its utility. However, we showed that superior results can be achieved when the natural frequency of the quadratic absorber is set equal to one-half the excitation frequency. Consequently, we applied the quadratic technique through a variety of linear and nonlinear actuators, sensors, and electronic devices.

We designed and built analog second-order circuits that emulate the quadratic absorber. Using a DC motor, piezoelectric ceramics, and Terfenol-D struts as actuators and potentiometers, strain gages, and accelerometers as sensors, we demonstrated successful single- and multi-mode vibration control.

In order to realize a more versatile implementation of the control strategy, we resorted to a digital signal processing (DSP) board. We composed a code in C and designed a digital absorber by developing algorithms that, in addition to replacing the analog circuit, automatically detect the amplitude and frequency of oscillation of the plant and fine-tune the absorber parameters. We took advantage of the digital realization, implemented a linear absorber, and compared the performance of the quadratic absorber with that of its linear counterpart.

In the case of parametric excitation, we investigated two techniques. First, we explore application of the quadratic absorber. We demonstrated theoretically and prove experimentally that this control scheme is not reliable. Then, we proposed an alternate approach. We devised a control law based on cubic velocity feedback. We conducted theoretical and experimental investigations and showed that the latter strategy leads to effective vibration suppression and bifurcation control.

## III. JOURNAL PUBLICATIONS

**1) North Carolina A&T State University and University of Missouri-Columbia:**

1. P. F. Pai, B. Wen, A. S. Naser, and M. J. Schulz, "Structural Vibration Control Using PZT Patches and Nonlinear Phenomena," *J. of Sound and Vibration 215(2)*, 273-296, 1998.
2. P. F. Pai and M. J. Schulz, "A Refined Nonlinear Vibration Absorber," *Int. J. of Mechanical Sciences*, in press.
3. M. J. Schulz, P. F. Pai, and D. J. Inman, "Health Monitoring and Active Control of Composite Structures Using Piezoceramic Patches," *Composites B Engineering*, in press.
4. P. F. Pai, "Geometrically Nonlinear Finite-Element Analysis of Trusses," *Int. J. for Numerical Methods in Engineering*, submitted.
5. P. F. Pai, B. Rommel, and M. J. Schulz, "Dynamics Regulation of a Skew Cantilever Plate Using PZT Patches and Saturation Phenomena," *IEEE Transactions on Control Systems Technology*, submitted.
6. P. F. Pai, B. Rommel, and M. J. Schulz, "Nonlinear Vibration Absorbers Using Higher-Order Internal Resonances," *J. of Sound and Vibration*, submitted.
7. C. R. Ashokkumar, A, Ghoshal, M. J. Sundaresan, M. J. Schulz, and M. Human, "Vibration Suppression using Reconfigurable Coordinate Velocities," *IEEE Transactions on Control System Technology*, submitted.
8. A. Ghoshal, E. A. Wheater, C. R. AshokKumar, M. J. Sundaresan, M.J. Schulz, M. Human, and P. F. Pai, "Vibration Suppression Using a Laser Vibrometer and PZT Patches," *Journal of Sound and Vibration*, submitted.

**2) Virginia Polytechnic Institute and State University:**

1. S. S. Oueini, A. H. Nayfeh, and M. F. Golnaraghi, "A Theoretical and Experimental Implementation of a Control Method Based on Saturation," *Nonlinear Dynamics 13 (2)*, 189-202, 1997.
2. S. S. Oueini, A. H. Nayfeh, and J. R. Pratt, "A Nonlinear Vibration Absorber for Flexible Structures," *Nonlinear Dynamics 15(3),* 259-282, 1998.
3. S. S. Oueini and A. H. Nayfeh, "Single-Mode Control of a Cantilever Beam under Principal Parametric Excitation," *Journal of Sound and Vibration*, accepted.
4. J. Pratt, S. Oueini, and A. H. Nayfeh, "A Terfenol-D Nonlinear Vibration Absorber," *Journal of Intelligent Material Systems and Structures*, accepted.
5. S. S. Oueini, C-M. Chin, and A. H. Nayfeh, "Dynamics of a Cubic Nonlinear Vibration Absorber," *Nonlinear Dynamics*, submitted.
6. S. S. Oueini, C-M. Chin, and A. H. Nayfeh, "Response of Two Quadratically-Coupled Oscillators to a Principal Parametric Excitation," *Nonlinear Dynamics*, submitted.

## IV. CONFERENCE PROCEEDINGS AND PRESENTATIONS

### 1) North Carolina A&T State University and University of Missouri-Columbia:

1. P. F. Pai, B. Wen, A. S. Naser, and M. J. Schulz, "Nonlinear Vibration Suppression of Cantilever Beams Using Bi-Moment Induced by PZT Actuators," 38th AIAA Structures, Structural Dynamics, and Materials Conference, Hyatt Orlando, Kissimmee, Florida, April 7-10, 1997.
2. P. F. Pai, B. Wen, and M. J. Schulz, "A Nonlinear Method for Vibration Control of Flexible Structures," Eleventh VPI&SU Symposium on Structural Dynamics and Control, Blacksburg, VA, May 12-14, 1997.
3. E. A. Wheater, A. S. Naser, M. J. Schulz, N. D. Wright, and P. F. Pai, "Active Vibration Control of Flexible Structures Using Rate Feedback," The 1998 NASA URC Technical Conference, Von Braun Center, Huntsville, Alabama, February 22-26, 1998.
4. P. F. Pai, B. Rommel, A. S. Naser, and M. J. Schulz, "Vibration Suppression of a Skew Cantilever Plate Using PZT Patches," SPIE's 5th Annual International Symposium on Smart Structures and Materials, Catamaran Resort Hotel, San Diego, California, March 1-5, 1998.
5. E. A. Wheater, M. J. Schulz, A. S. Naser, K. W. Waldron, and P. F. Pai, "Active Vibration Control of Flexible Structures Using Piezoceramic Patches and a Laser Vibrometer," 5th International Conference on Composites Engineering, Las Vegas, Nevada, July 5-11, 1998.
6. P. F. Pai, B. Rommel, and M. J. Schulz, "Structural Vibration Suppression Using PZT Patches and Higher-Order Saturation Phenomena," SPIE's 6th Annual International Symposium on Smart Structures and Materials, Newport Beach, California, March 1-5, 1999.
7. E. A. Wheater, A. Ghoshal, C. R. Ashokkumar, M. J. Sundaresan, M. J. Schulz, and P. F. Pai, "Vibration Suppression Using a Scanning Laser Vibrometer and Piezoceramic Patches," 4th ARO Workshop on Smart Structures, The Pennsylvania State University, University Park, PA, August 16-18, 1999.

### 2) Virginia Polytechnic Institute and State University:

1. J. Pratt, S. Oueini, and A. H. Nayfeh, "A Terfenol-D Nonlinear Vibration Absorber," SPIE's 4th Annual Symposium on Smart Structures and Materials, San Diego, CA, March 3-6, 1997.
2. J. Pratt and A. H. Nayfeh, "Active Vibration Control for Chatter Suppression," Structural Dynamics and Materials Conference, AIAA Paper No. 97-1207, Kissimmee, FL, April 7-10. 1997.
3. S. S. Oueini and A. H. Nayfeh, "Multimode Control of Flexible Structures." Structural Dynamics and Materials Conference, AIAA Paper No. 97-1207, Kissimmee, FL, April 7-10, 1997.
4. A. H. Nayfeh and J. Pratt, "Chatter Identification and Control for a Boring Process," IUTAM Symposium on New Applications of Nonlinear and Chaotic Dynamics in Mechanics, Cornell Univ., July 27-August 1, 1997.

5. S. S. Oueini and A. H. Nayfeh, "An Active Nonlinear Vibration Absorber," Third ARO Workshop on Smart Structures, Virginia Tech, Blacksburg, VA, August 27-29, 1997.
6. S. S. Oueini and A. H. Nayfeh, "Control of a System Under Principal Parametric Excitation," The Fourth International Conference on Motion and Vibration Control, Zurich, Switzerland, August 25-28,1998.
7. S. S. Oueini, C-M. Chin, and A. H. Nayfeh, "Dynamics of a Cubic Nonlinear Vibration Absorber," ASME 17th Biennial Conference on Mechanical Vibration and Noise, Symposium on Dynamics and Control of Nonlinear Systems, Las Vegas, NV, September 12-15, 1999.

## V. DEGREES GRANTED AND STUDENT PARTICIPATION

### 1) North Carolina A&T State University and University of Missouri-Columbia:

- B. G. Rommel, 1999, M.S., "Vibration Suppression of a Skew Cantilever Plate Using Nonlinear Vibration Absorbers."

Student Participation without degree:
- Bing Wen, MS student, performed experimentation.
- David Jeffers, UG ME student, helped build laser experiment, supported by leveraged grant, to graduate with BS 1999.
- Maurice Heath, UG ME student, helped build laser experiment, supported by leveraged grant, to graduate with BS 1999.
- Eric Wheater, Ph.D. ME student, built laser scanner, performed experiments.

### 2) Virginia Polytechnic Institute and State University:

- J. Pratt, 1997, Ph.D., "Vibration Control for Chatter Suppression with Application to Boring Bars"
- S. S. Oueini, 1998, Ph.D., "Techniques for Controlling Structural Vibrations"